FUSION FOR NEUTRONS (F4N)

- A REALISABLE FUSION NEUTRON SOURCE

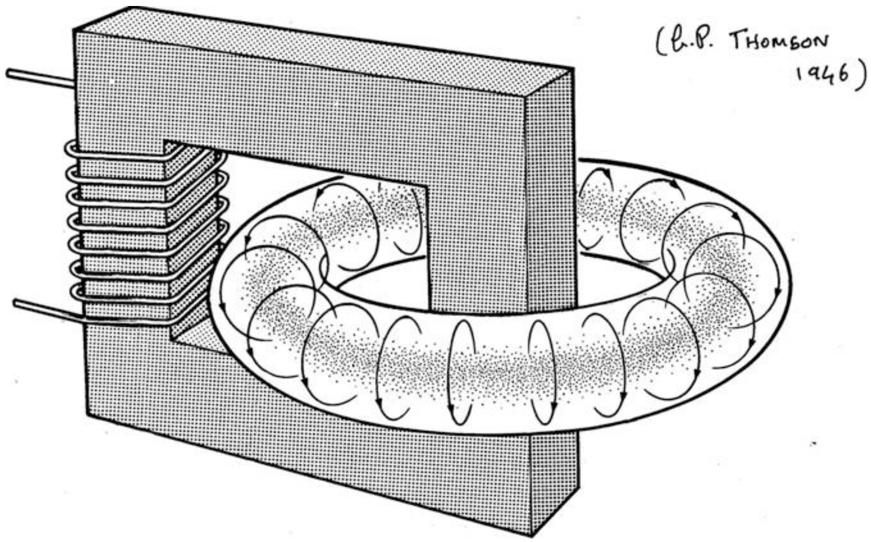
A. Sykes, M.P. Gryaznevich, G. Voss, D. Kingham, B. Kuteev [1]

Tokamak Solutions UK, Culham Science Centre, Abingdon, UK

[1] RRC Kurchatov Institute, Moscow, Russia

The 1946 Thomson, Blackman patent for a Fusion Reactor

"..a powerful neutron source …. Also a powerful source of heat"



Based on a toroidal Pinch. Parameters were modest:

R / a = 1.30m / 0.3m, I_p = 0.5MA

classical confinement was assumed :

→τ = 65s →T = 500keV

Hence D-D fusion would be achievable

(note: Patent includes option of Uranium or Thorium blanket – i.e. a hybrid!)

ZETA at Harwell, 1954-1968 :

R/a=1.50m / 0.48m, I_p = 0.1 – 0.9MA

Confinement was highly anomalous:

τ ~ 1ms → T~ 0.16keV

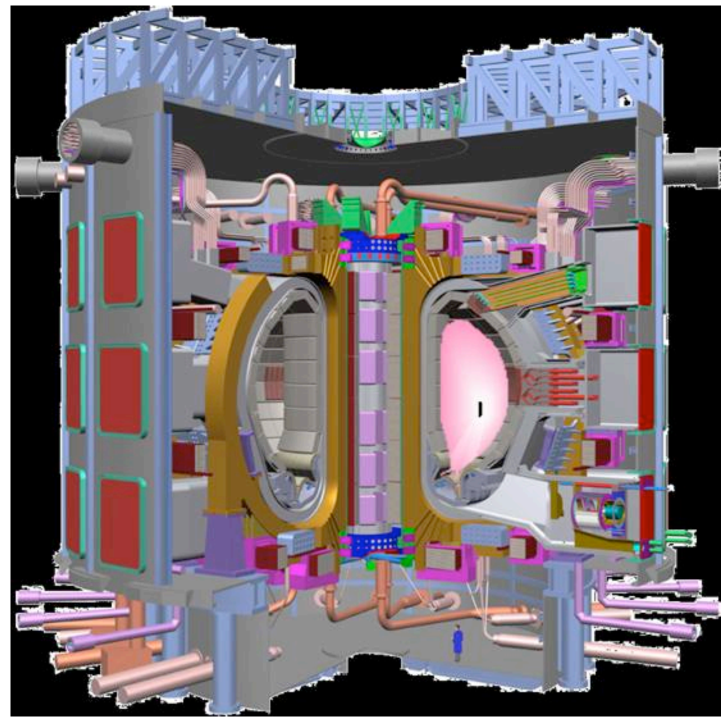
- Beginning of a long path to fusion energy!

Developments and improvements have led to the **Tokamak** and the stabilisation of countless plasma instabilities – kink modes, ballooning modes, tearing modes…and the identification of several key limits – current limit, density limit, beta limit….

But energy confinement τ still anomalous!
Empirically, scales (very approx) as

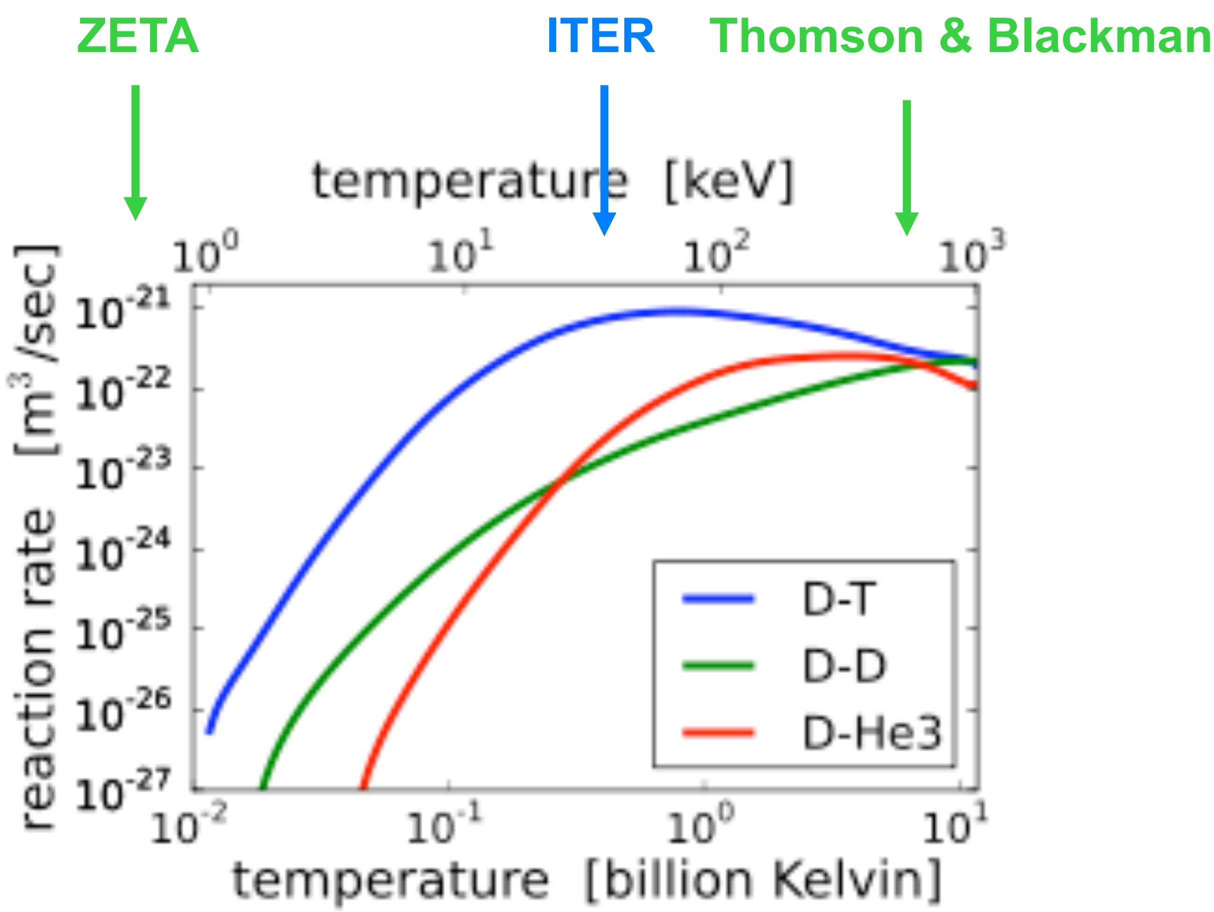
$$\tau \sim R^2 \times I \times B$$

– leading to the ITER project
$R / a = 6.2$m / 2m, Vol ~ 850m^3, I = 15MA,
B_T (at R) = 5.3T, τ ~ 3.5s, T_e ~ 25keV



The large volume of ITER increases the confinement time; and the high I and B help contain the charged ^{4}He particles, which further heat the plasma

$$D + T \rightarrow n\ (14.06\ \text{MeV}) + {}^4He(3.52\ \text{MeV})$$



D - D fusion

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV)

D-T fusion

D + T → n (14.06 MeV) + ^{4}He(3.52 MeV)

Fusion for Energy is difficult:

For economic energy, we need: tritium, large size to obtain hot fusing plasma; high fields and large currents

→ high build & running costs, large stored energy (beware disruptions, ELMs)

Fusion for NEUTRONS (F4N) may be easier!

Fusion produces many neutrons

$D^2 + T^3 \rightarrow {}^4He + n + 17.6$ MeV   5 amu → ~3.5MeV plus 1 neutron of 14.1MeV

Fission produces few neutrons

$U^{235} + n \rightarrow Ba^{144} + Kr^{89} + 3n + 200$ MeV   5 amu → ~4MeV + 0.04 neutrons of ~ 2MeV

Many applications: e.g. as neutron sources for research (e.g. materials research); deep penetration diagnostics including security scanning; production of medical isotopes etc – AND…

- applications of Fusion neutrons to Fission

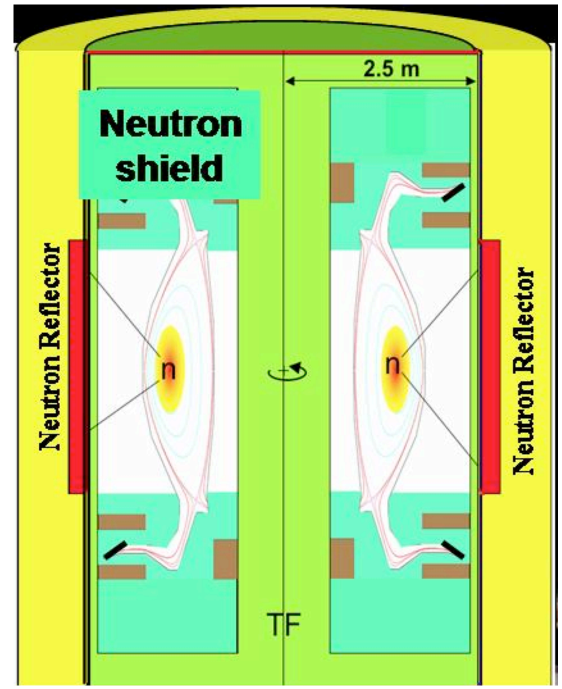
Fusion's 14MeV neutrons could make 4 major contributions to Fission:

(1) Conversion of 'spent' fuel (and depleted Uranium) into fissile fuel

(2) Transmute the most dangerous waste, minimising storage demands

(3) Supplying neutrons to power a sub-critical fission plant: a 'hybrid'– improving fail-safe options*

(4) Supplying neutrons for starting-up and topping-up a thorium cycle plant



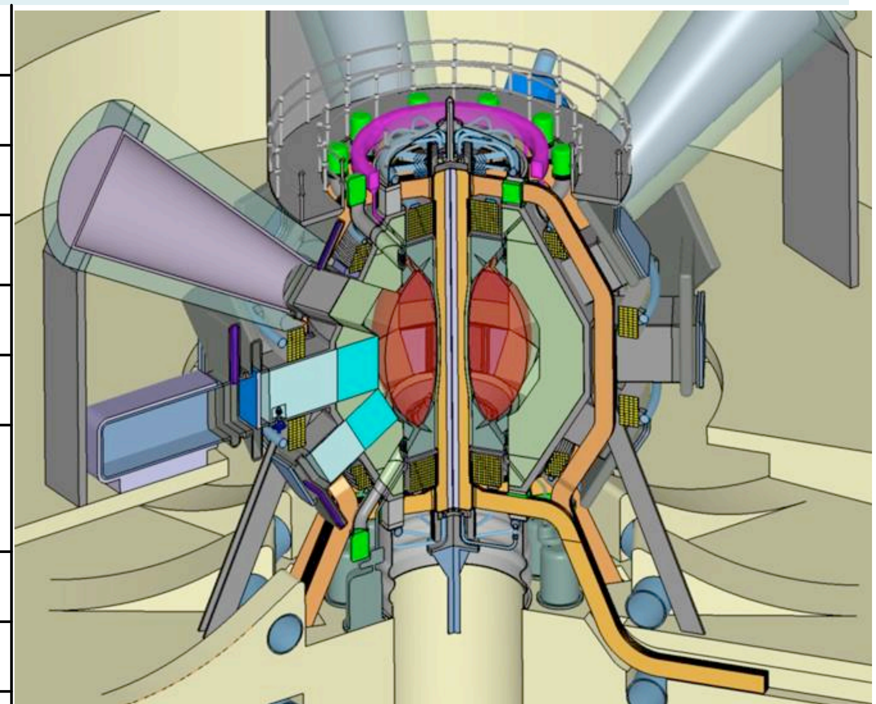
The ST offers a compact solution to the 'fusion within fission' hybrid (e.g. this Univ of Texas concept)

****H. Bethe**, "The Fusion Hybrid," Physics Today **32**, No. 5, 44 (1979). **P H Rebut:** 'From JET to the reactor', EPS meeting, Rome, June 2006.*

- and Component Test Facilities to aid the Fusion for Energy programme… e.g. the Culham CTF

Parameter	ST-CTF
Major / minor radius	85/55cm
Elongation / triangularity	2.4/0.4
Plasma current/rod current	6.5/10.5MA
β_N	3.5
Average density	1.8×10^{20} m^{-3}
Average temperature	Te=6.5keV Ti=8keV
Confinement H98(y,2)	1.3
Auxiliary power	40MW
Fusion power (thermal + b-p)	35MW
Neutron wall loading	$1MWm^{-2}$

Ref: G Voss et al, ISFNT8 conf 2007, Fusion Engineering and Design 83 (2008) 1648–1653



Tritium consumption ~ 0.6 kg/y
does not need to breed tritium

US (PPPL, ORNL, Texas) plan a larger CTF, with blanket for breeding tritium

Challenges for the CTF

High neutron yield for long pulses is required to achieve the objective of component testing

→ high NBI power for heating & current drive, and high field & plasma current to maximize confinement

→ high wall load (requiring special material development?) and high build and operating costs

And, **start-up and ramp-up are not yet fully demonstrated**

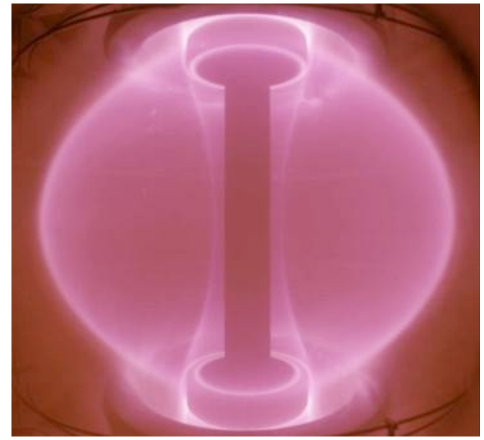
These demands have delayed building of the first CTF, despite widespread demand for such a facility

What is the minimum cost device able to demonstrate the basic features – say 1MW of neutron production in long pulse operation?

Two key features: the **spherical tokamak** and **beam-plasma fusion**

The Spherical Tokamak

The Spherical Tokamak (ST) is a version of the tokamak where the central stack, containing the TF magnet and (usually) solenoid, is shrunk to small size.

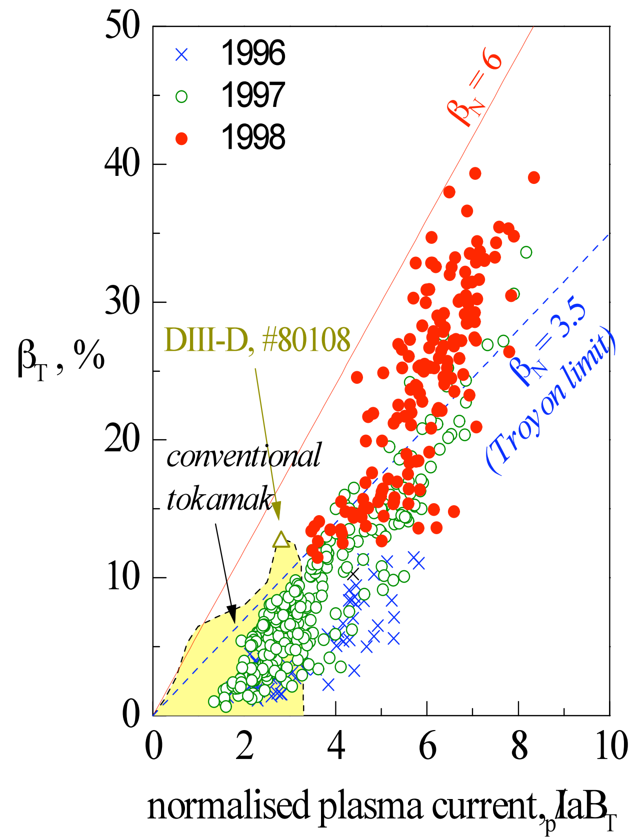


Advantages as a neutron source:

high neutron wall load for the least tritium;

has enhanced stability properties;

and has achieved record highest beta (efficiency) values.



Challenges as a neutron source:

protection of the centre column from neutron damage (no space for full shielding)

- How to provide TF, and how to start-up and ramp-up the plasma current

High field STs

To date, ST experiments have (successfully) exploited the advantages of high currents at low magnetic field, and natural plasma shaping

BUT….. for fusion applications we need HIGH field!

e.g. 'triple product' $n\,T\,\tau$: each term ~ B

Fortunately, indications are that STs perform even better at high field:

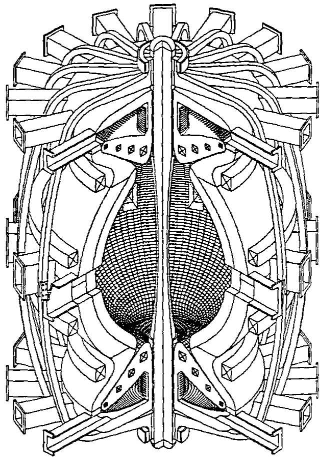
Stability - increases with B_T;

Confinement - although present ITER scaling has $\tau \sim B_T^{\,0.15}$, latest results** from NSTX, MAST indicate much stronger dependence $\tau \sim B_T^{\,1.3}$ (MAST), $B_T^{\,0.91}$ (NSTX)

Neutron production – increases strongly with B_T

both MAST and NSTX are planning upgrades to increase B_T from ~ 0.5T to ~1T

*Stan Kaye, PPPL, Martin Valovic UKAEA Plasma Phys. Control. Fusion **48** (2006) A429–A438*

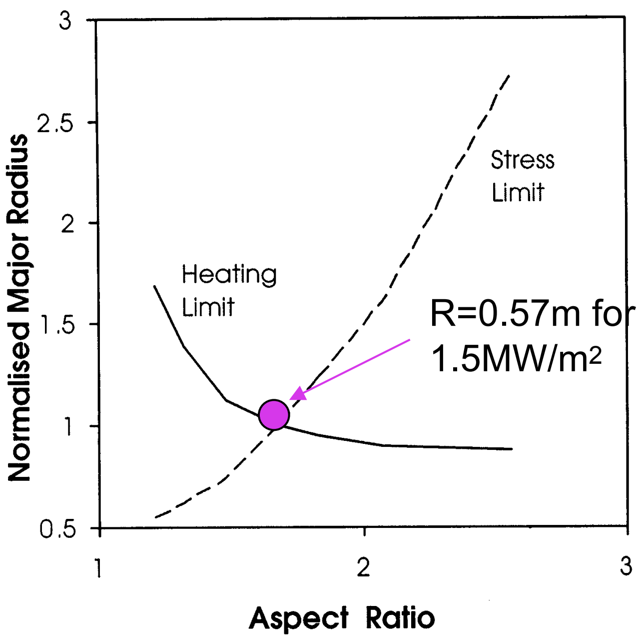


Peng-Hicks concept for ST power plant (1990)

using an unshielded, single-turn copper centre rod

Optimum ST

Hender, Voss & Taylor [1] combined physics, engineering and neutronics considerations to scope the optimum aspect ratio and size



Normalised device size as a function of aspect ratio at fixed neutron wall load, β_N and q_{95} = 3 (from [1]). The major radius has to be higher than both limits.

At lower performance levels than 1.5MW/m^2, smaller devices become feasible.

[1] *T.C.Hender et al, FED 45 (1999) p265*

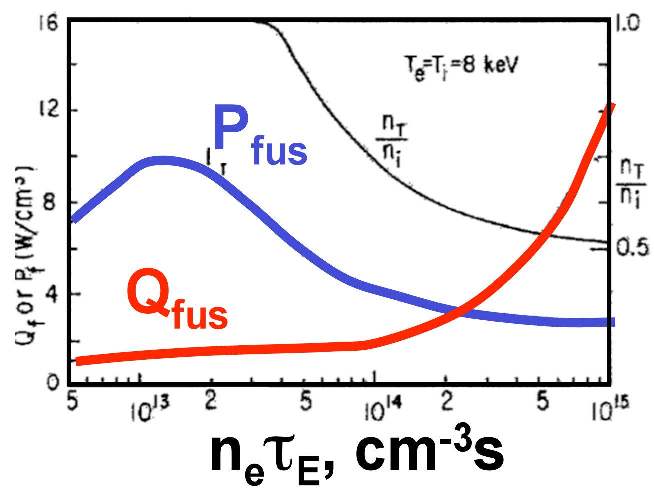
Beam – Plasma Fusion

For energy production, we need thermal fusion in high temperature plasmas, α heating– hence large size, high current, high TF.

However injection of high energy (~100keV) D or T neutral beams can produce fusion even in a merely 'warm' (say 1keV) plasma: an effect described by Jassby *Nuclear Fusion,* ***15*** *(1975) 453*

Jassby showed that maximum neutron production and maximum efficiency Q can be realized at different plasma conditions:

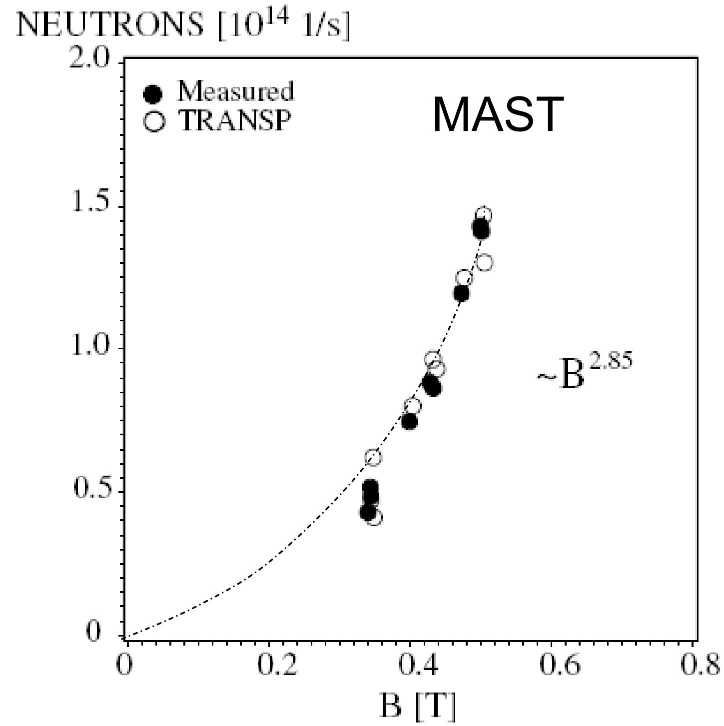
the fusion rate P_{fus} can be large at modest $n\tau_E$ ~10^{13} cm^{-3} s, while electricity production requires high efficiency Q_{fus} ($Q_{fus} = P_{fus}/P_{in}$), and so higher values of $n\tau_E$



Beam – Plasma Fusion

IT WORKS!

Beam – plasma fusion is significant in JET D-D experiments (typically accounting for 50% of neutrons produced) and dominant in MAST (also D-D), accounting for most neutrons

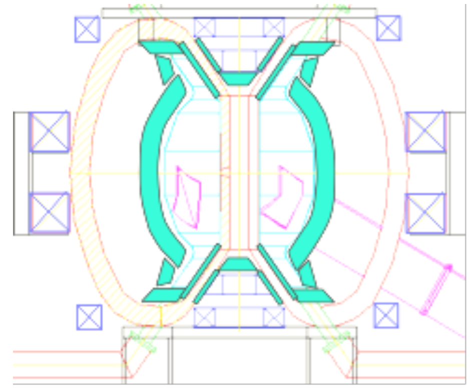


*Neutron emission (2.45MeV) from MAST (Valovic et al, NF **51** (2011) 073045)*

small-scale neutron sources become possible: e.g. a **S**uper **C**ompact **F**usion **N**eutron **S**ource **SCFNS** with major radius as low as R=0.5m

B-scan with q=const, n=const and beam power increasing by 10% to provideT~B^2. At highest B, I_p=0.9MA, P_{NBI} =3.4MW

Super-Compact Fusion Neutron Source



	MAST/ MAST-U UK	NSTX/ NSTX-U US	Globus-M/ Globus-MU RF	QUEST Japan	KTM Kazak hstan	SCFNS TSUK UK
R, m	0.8	0.75/0.75	0.36	0.68	1.0	0.5
R/a	1.4	1.3/1.5	1.5	1.7	2.0	1.6
k	2.7/2.75	2.8/2.8	1.6	2.5	2	2.7
I_p, MA	1.4/2	1.5/2	0.35	0.3	0.5	1-2
B_t, T	0.6/0.8	0.5/1	0.5	0.25	1	1.5
P_{NB}, MW	4/10	7/10	1.5	-	-	5-10
t_{pulse}, s	0.8/5	1.8/5	0.5	s/s	0.5	s/s

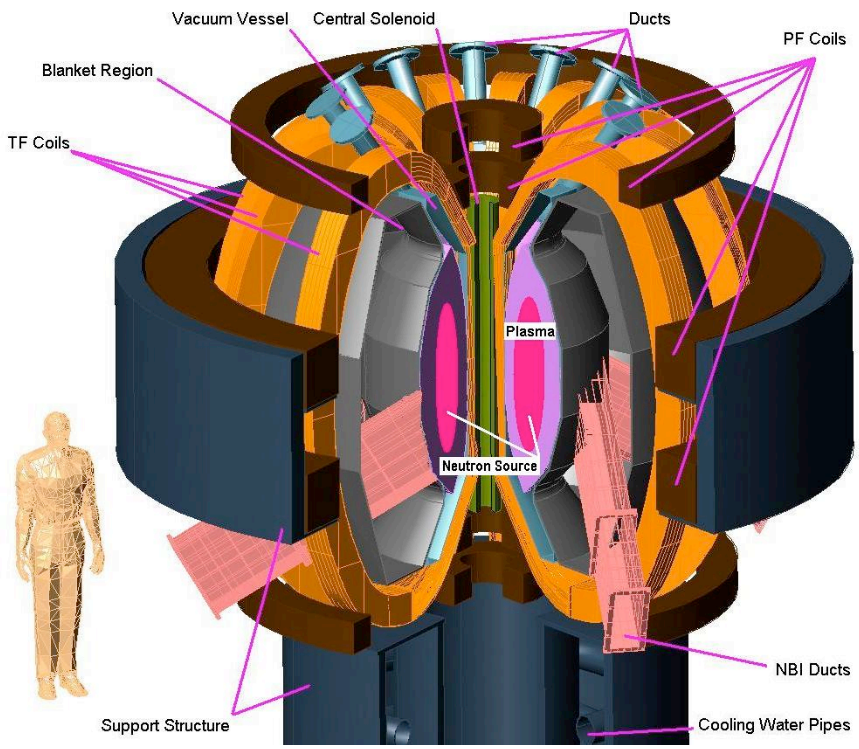
Comparison of SCFNS parameters with those of leading STs

Except for the higher toroidal field and the long pulse, SCFNS parameters are an interpolation of present STs

For a R=0.5 device, the operating stresses limit SCFNS to 1.5T at R=0.5.
This is a disadvantage of small size: max B_T increases with device size

Details of SCFNS [1]

R(m)	0.5
R/a	1.66
κ	2.75
δ	0.5
Ip(MA)	1.5
B_T(T)	1.5
P_b(MW)	6
E_b(keV)	130
Swall (m^2)	13
Vplasma(m^3)	2.5
PdissTF (MW)	14
Pdiss PF (MW)	3.5
Pwall (MW/m^2)	0.2
Pfus (D-T)	1-2MW



T_{eo}, T_{io} ~ 4.7, 7.9 keV

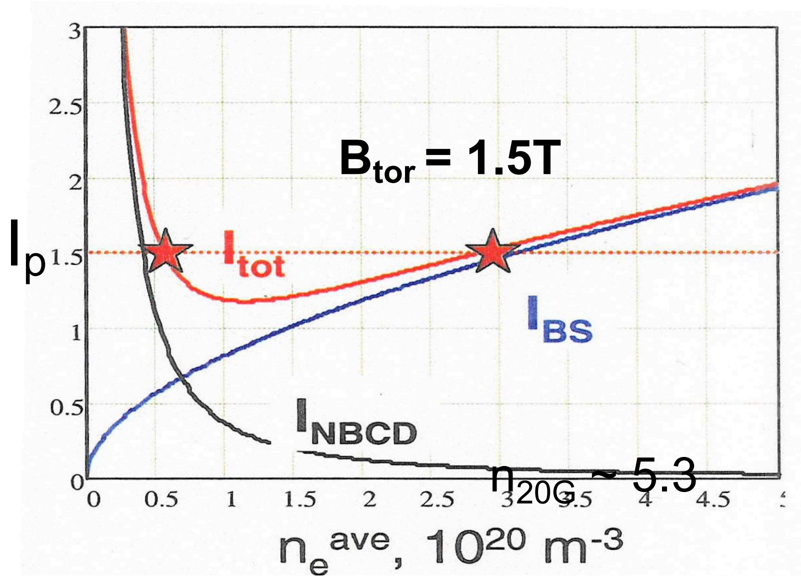
β_N ~ 4.9 τ_E ~ 43ms

H-factor ~ 1.3

At such low input power wall and divertor loads are manageable

[1] Kuteev et al, NF 51 073013 (2011)

Extensive modeling has been undertaken for B_T = 1.5T:

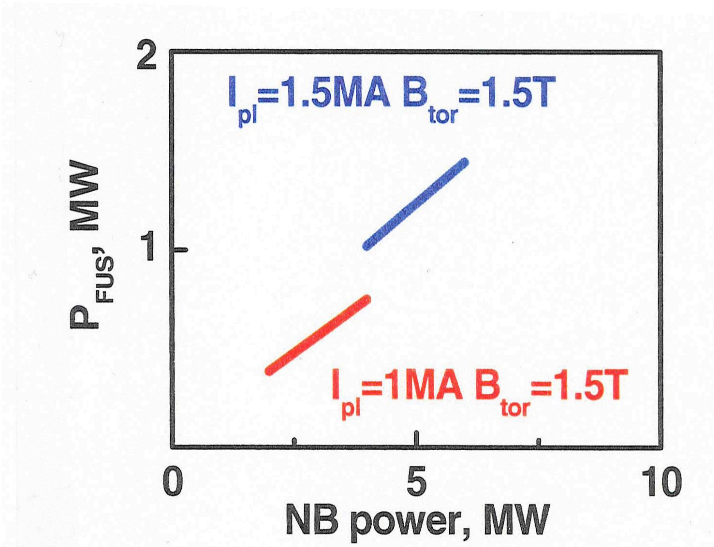


Steady – state operation of SCFNS

Modelling using ASTRA, DINA and semi-analytic models [1] indicates that 6MW of NBI can maintain plasma current around 1.5MA both at low density (where NB CD dominates) and at higher density (where bootstrap dominates)

Neutron yield in SCFNS

the simulations predict that ~ 1MW of fusion neutrons will be produced during D-T operation

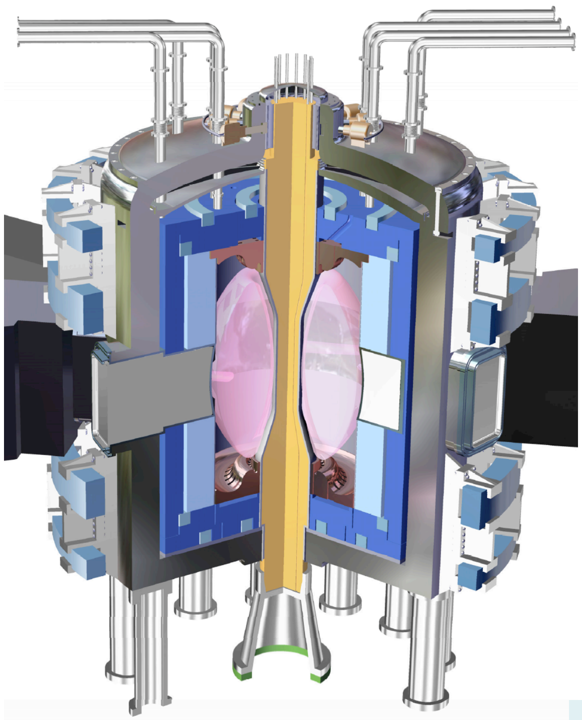


[1] Kuteev et al, NF 51 073013 (2011)

FNSF-ST (Martin Peng, S04A2, Thursday am)

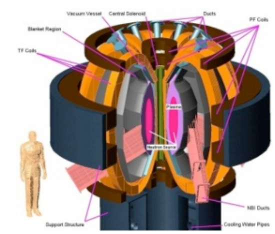
FNSF-ST is a major facility that can test the challenges of start-up, ramp-up and long pulse operation, AND can be upgraded to a full CTF

FNSF-ST	R=1.3, a=0.75	vol ~ 42m^3	S~75m^2	P_{NBI} =26MW	P/vol ~ 0.6MW/m^3	P/S ~ 0.3
SCFNS	R=0.5 a=0.3	vol ~ 2.5m^3	S~12m^2	P_{NBI} ~ 6	P/vol ~ 2.4MW/m^3	P/S ~ 0.5



FNSF-ST

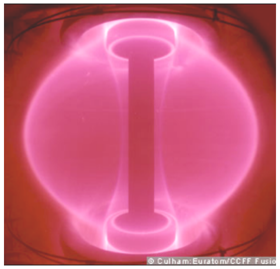
It is estimated that approx 450 research fission devices were built to test out fission concepts – approximately the same number as operational reactors



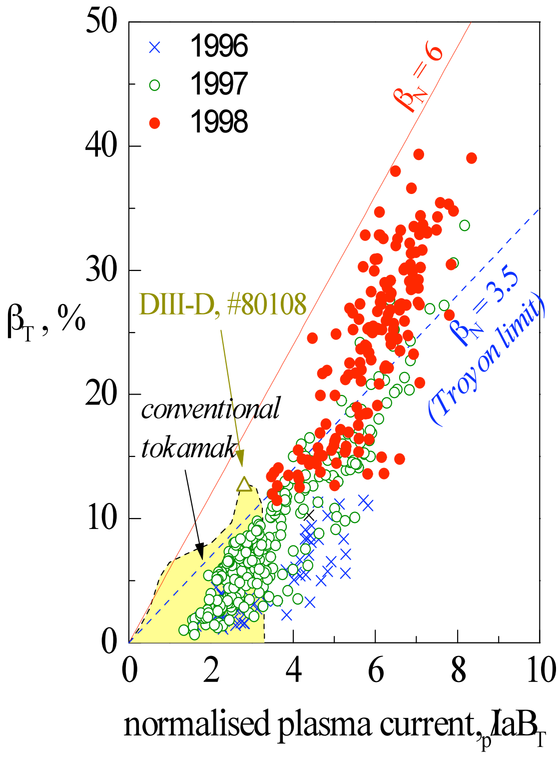
SCFNS

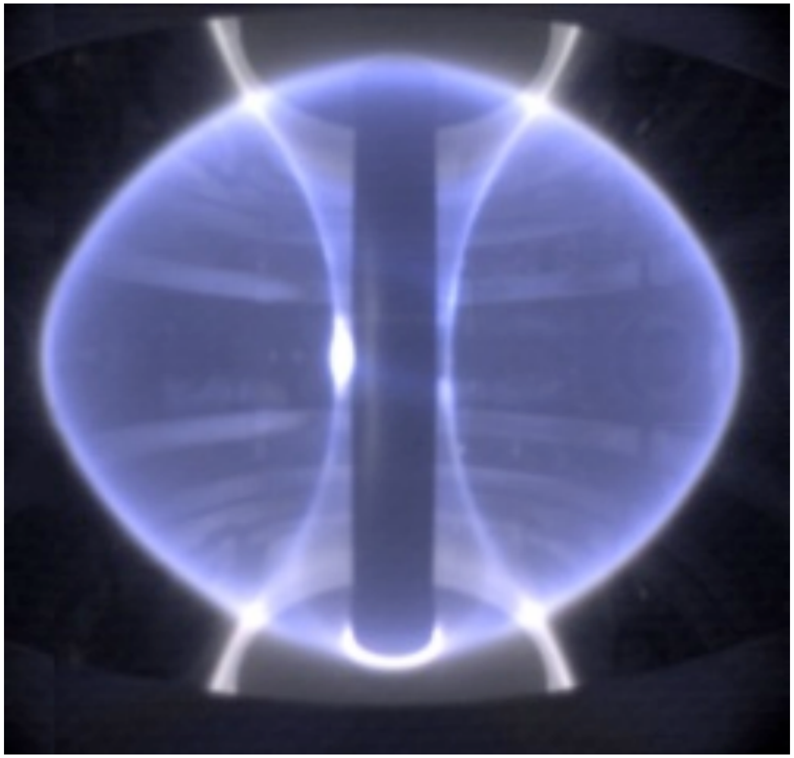
FNST-ST and SCFNS are two of the many devices needed to advance fusion !

Note: much can be accomplished in a small device!

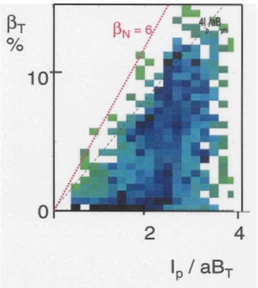


START: P_{NBI} = 1MW plasma vol ~ 0.6m^3





MAST: P_{NBI} ~ 3MW plasma vol ~ 10m^3

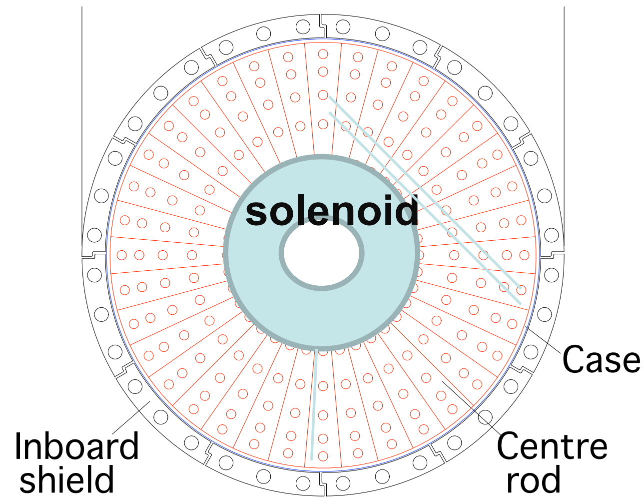


Challenges: Start – up and Ramp – up

In compact ST devices such as SCFNS, under D-T operation there is no space for adequate shielding to protect a conventional central solenoid

Three suggestions for **start-up**:

1) Use a solenoid - either retractable or using radiation resistant insulation (requires use of segmented c/col to minimise eddy currents)



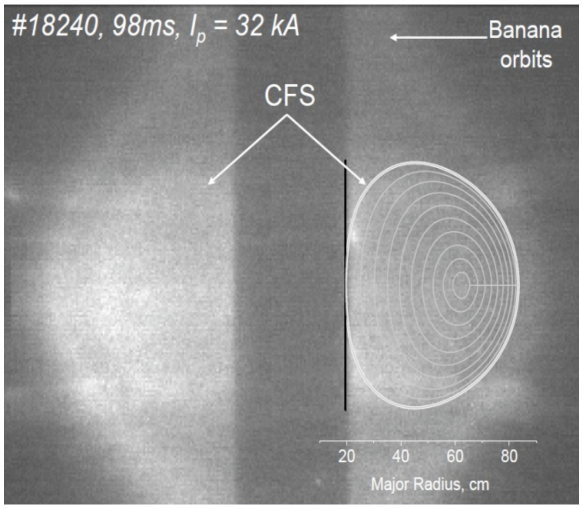
2) Use RF methods, e.g. Electron Bernstein Wave (EBW)

3) Use more novel methods – in-vessel coils (as in Culham VNS proposal), external coils (Univ. Tokyo), external PF (DIII-D, JT60), helicity injection,….

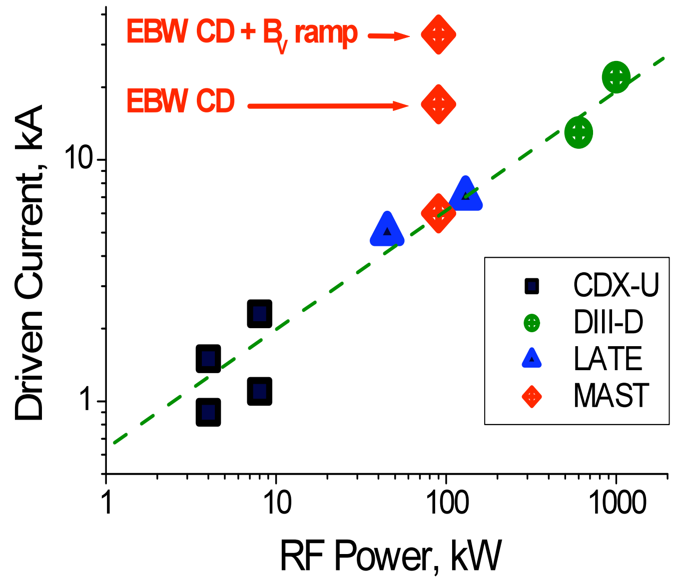
For **ramp-up**, NBI is very effective – especially by heating the plasma….

Start – up (1)

RF methods – EBW shows promise on MAST (V Shevchenko et al., NF **50** (2010) 022004)



CCD image of an EBW-produced plasma in MAST showing (left) closed flux surface, and (right) magnetic equilibrium reconstruction



RF start-up on various tokamaks. The EBW scheme is shown to be especially effective, producing 33kA plasma current for input power of 100kW on MAST

For higher field devices, slightly higher efficiencies are expected.
Optimal frequency ~ 46 GHz for 1.5T, requiring mirror size ~ 13cm diam

Ramp – up

Although NBI can produce direct current drive, its biggest effect during ramp up is to HEAT the plasma. This means the vertical field has to increase to contain the expanding plasma: this inputs inductive flux

Examples observed in MAST experiments when inductive drive from the central solenoid is applied to maintain an established plasma.

For Ohmic discharges approx 1.4V is required;

for low NBI powers ~ 1MW about 0.9V is required;

for higher power ~ 2.6MW only about 0.1V is required.

The implication is that application of higher NBI power on MAST should increase the plasma current without input from the central solenoid.

SCFNS would have (NBI Power) / vol ratio EIGHT TIMES greater than MAST and so ramp-up should be very effective

The 1946 Thomson, Blackman vision: Small device, D-D fusion

For neutron sources, beam-plasma fusion means that devices can be small. The main handicap to immediate progress is the cost and safety implications of tritium.

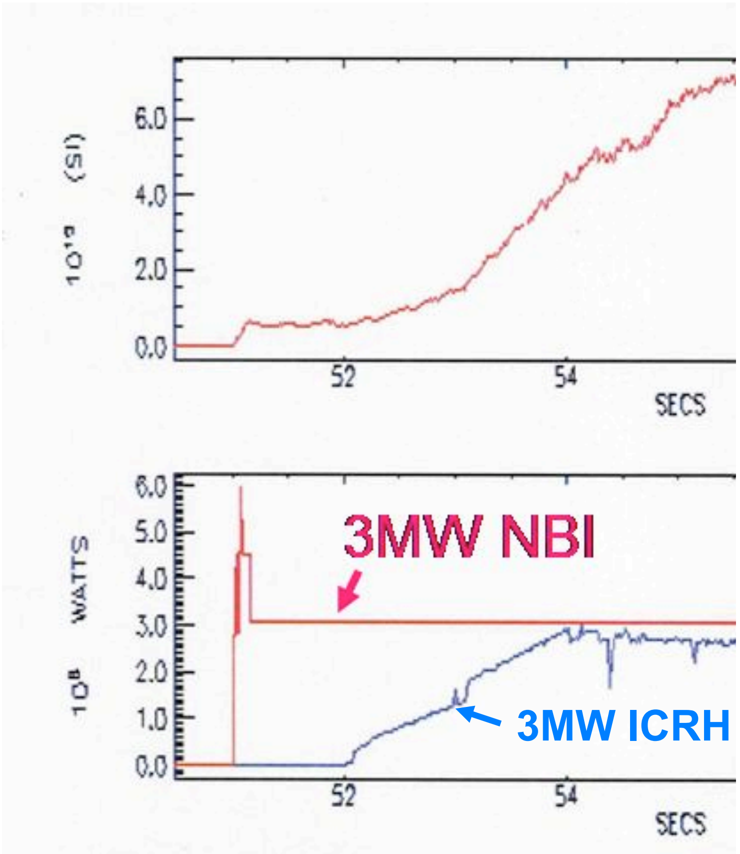
To make rapid progress, and to resolve start-up, ramp-up and current drive, operation in D-D provides big advantages!

D-D means 80x – 100x fewer neutrons - can D-D fusion be optimised?

Optimisation 1: use higher energy NBI *or* increase NBI deuteron energy by ICRH or HHFW.

Optimisation 2: if no (or small) neutron damage, stress limits on c/col can be relaxed – so B_T can be increased

Increase the NBI deuteron energy , e.g. using ICRH as on JET:



JET #74937: addition of 3MW ICRH to 3MW NBI (120keV) increased D-D fusion 10-fold, from 0.7×10^{15} to 7×10^{15}/s

with neutron energies of up to 6MeV

- " a viable candidate for a driven neutron source without the need to use tritium" *(C Hellesen et al, Nuclear Fusion 50 (2010) 022001)*

Fusion neutron source – build costs

1.	CTF [1]	D-T	10^{19} n/s	s/s	cost ~ $1B
2.	SCFNS [2]	D-T	$5x10^{17}$ n/s	s/s	cost ~ $200M
3.	SCFNS	D-D	10^{16} n/s	s/s	cost ~ $100M
4.	MAST-U [3] / NSTX-U [4] (coming soon)	D-D	10^{15} n/s	pulsed	cost ~ $50M extra
5.	MAST/NSTX	D-D	10^{14} n/s	pulsed	HERE NOW!

*[1] M.Peng et al, PPCF **47** (2005) B263* *[2] B Kuteev et al, Plasma Physics Reports **36** (2010) p281*
[3] William Morris, invited paper, Weds *[4] Jon Menard, invited paper, Weds*

<u>Cost of neutrons in SCFNS!</u>

Electrical power = 18MW(diss) +18MW (NBI) ~ 36MW For 1 sec operation, 36,000kW for 1/3600th hr = 10kWh ~ $1……….. Hence **$10^{17}$ neutrons = $1**

Tritium: assuming $100M per kg → **5c per 10^{17} neutrons**

Summary

'Fusion for neutrons' could provide a near-term application of fusion

Small devices appear possible, utilising beam-plasma fusion

A small neutron source, SCFNS, is proposed, designed to validate the concept
Modelling predicts that it can run ~ steady state at modest field and plasma parameters and modest NBI power, with neutron yield of 1-2MW for D-T operation

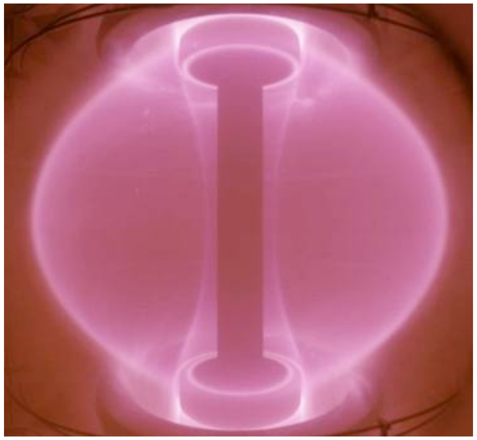
At these parameters, wall and divertor loadings are within those considered acceptable for ITER. Plasma stored energy is within that already experienced on MAST and NSTX, so that disruptions and ELMs will not cause damage

An even simpler and cheaper first step is to operate in D-D which will test all the properties of SCFNS

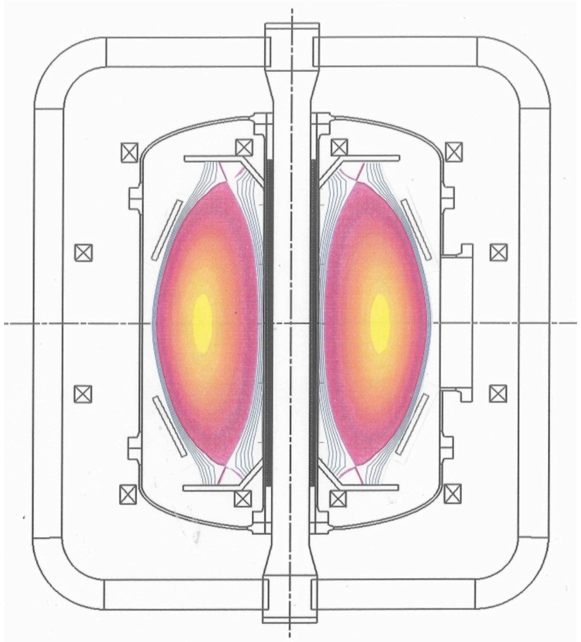
Summary

"Fusion for Neutrons" (F4N) is bringing new impetus to Fusion Research

- Including new interest in small STs both for basic research – and into new studies of beam-plasma fusion

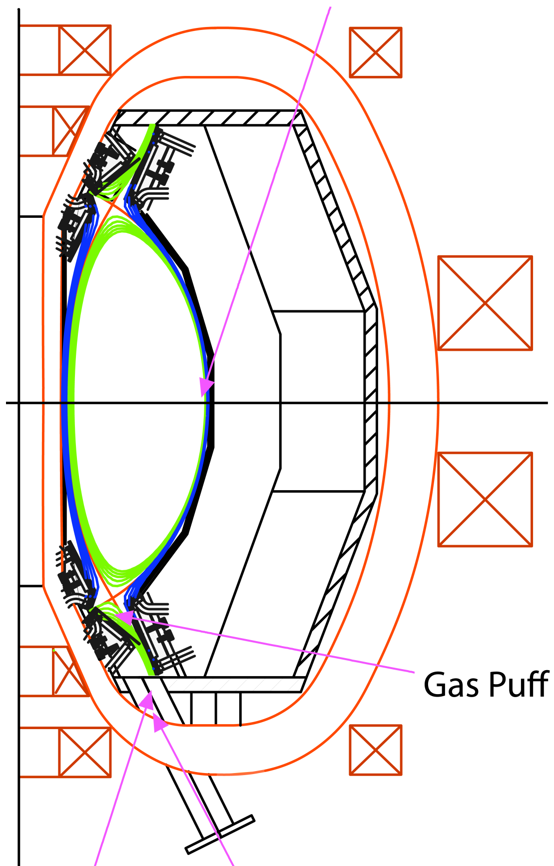


Plasma in START



Design of PRST30 (TSUK Ltd)

Divertor, wall loading



Divertor loading and wall loading are comparable to those in ITER

Expanded divertor / super-X divertor, and / or lithium dust jets, may be useful

At the low fields of SCFNS, the 3.4MeV α-particles from D-T fusion are poorly confined; however being initiated throughout the plasma, orbit modelling suggests they should hit the first wall over a wide area.

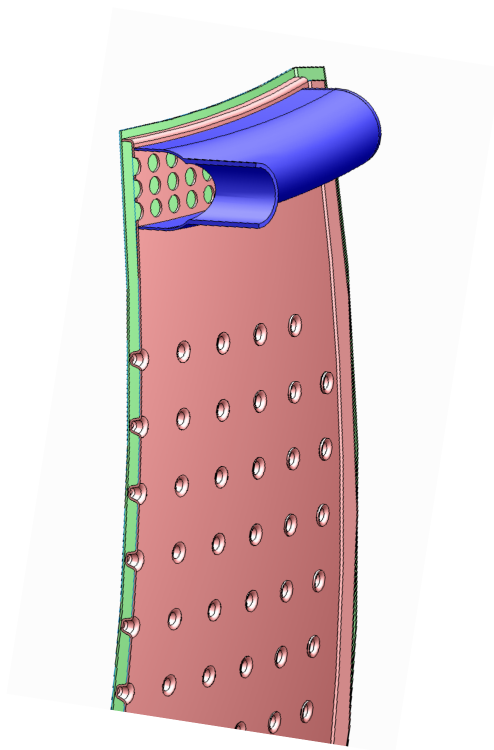
In D-D operation the He^3 particles are of much lower energy (0.82MeV) – and hence also better contained

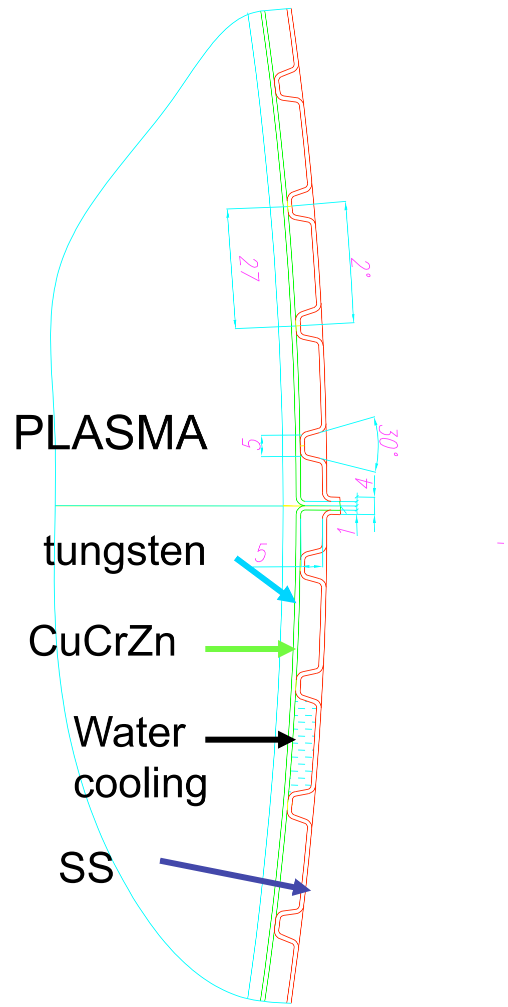
B. Kuteev et al, Steady State Operation in Compact Tokamaks, 6th IAEA TM Jan 2011

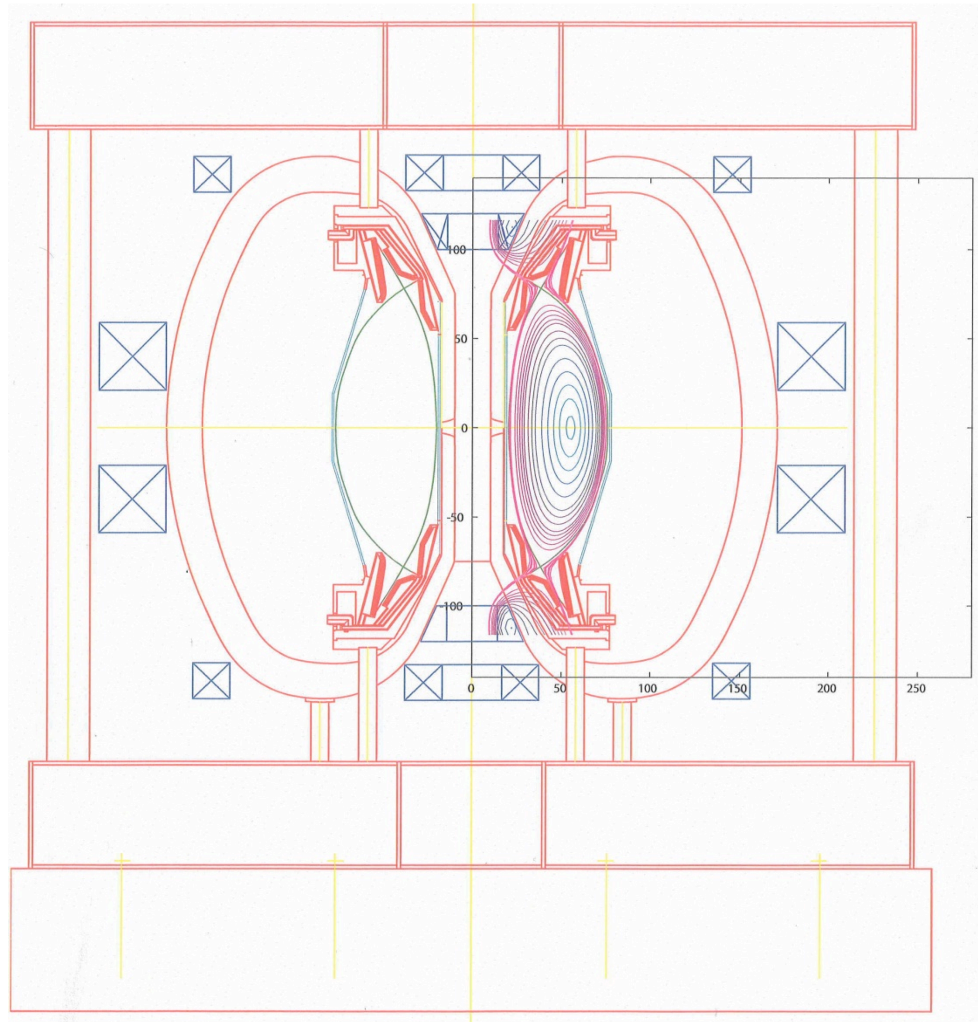
First Wall designs for SCFNS

Still evolving.

Plan to use techniques used in ITER divertor for both walls and divertor in SCFNS (no Be wall tiles in SCFNS)







100
50
0
-50
-100
0
50
100
150
200
250

Comparison with MAST

The estimates of Pfus =1 - 2 MW are produced using the latest codes, validated by comparisons with JET, etc.

But we can get an independent estimate from MAST, which has produced $1.5x10^{14}$ n/s at B_T = 0.5T using 3MW of NBI, with neutron production observed to scale as $B_T^{\ 2.85}$.

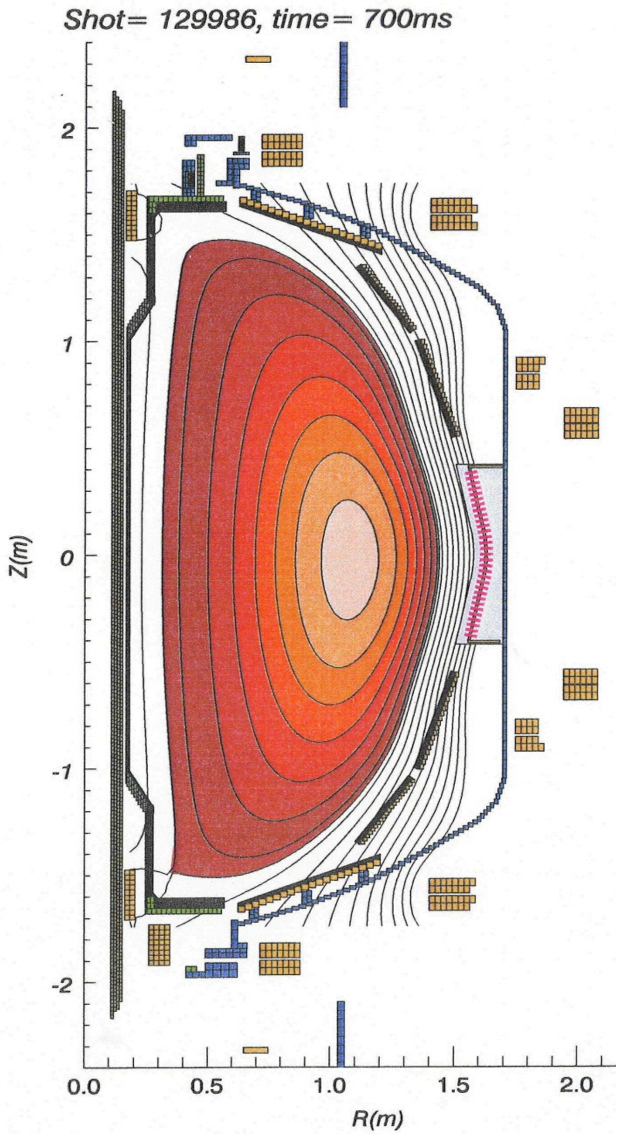
If we extrapolate these MAST results [1] , SCFNS at 1.5T and doubled PNBI would expect $3^{\ 2.85}$ = 23 increase from field; and x80 increase from using D-T rather than D-D.

This is a total increase of 1840, suggesting $2.8x10^{17}$ neutrons – i.e. about 1MW . An additional increase ~x2 is expected due to increase in NBI energy

- Consistent with the modelling

[1] assuming that the scaling applies at the lower collisionality of SCFNS; that energetic particle modes are not excessive; …….

Recent ST highlights support SCFNS design features

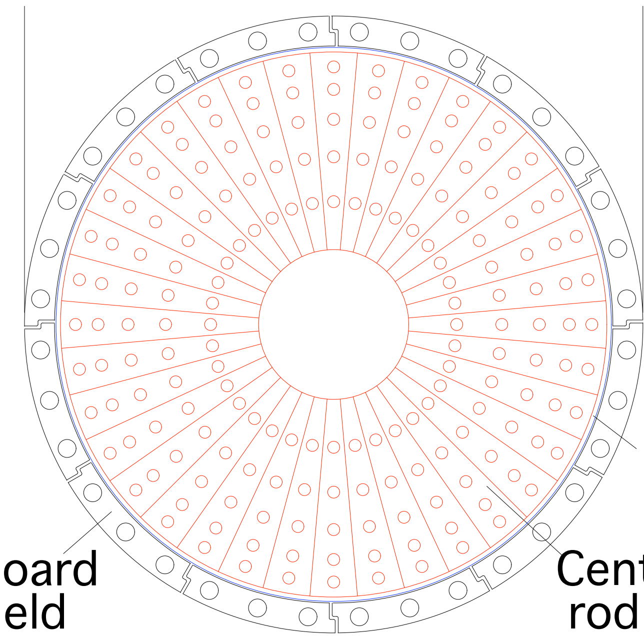


Equilibrium reconstruction of long-pulse discharge in NSTX [D.Gates et al, NF **49** (2009) 104016]. These discharges achieve κ ~ 2.75 at β_N ~ 5.5 for 0.5s, with high bootstrap fraction ~ 50%.

The duration was only limited by the heating limits of the TF coil.

plasma aspect ratio ~ 1.53

Centre column design - TF [1]



36-segment (segments used to ease manufacture – they are not insulated from each other) solid copper c/col with transformer-rectifiers on return limbs
To give TF =1.5T at R=0.5 requires total c/col current 3.75MA

Copper is embrittled when exposed to neutron fluence (even 0.01 – 0.1 dpa). Feltmetal sliding joints minimise axial tensile stresses in the rod, and aid maintenance.

For a R=0.5 device, the operating stresses limit SCFNS to 1.5T at R=0.5.
This is a disadvantage of small size: max B_T increases with device size

[1] Conceptual design of a CTF based on the ST, G.M. Voss et al, FED **83** (2008) 1648–1653

Experiments on MAST-Upgrade (William Morris, invited paper, Weds)

MAST-Upgrade will have improved plasma shaping and improved vacuum conditioning (hence low li, elongated plasmas, high bootstrap); increased TF (from 0.55 to 0.8T); increased NBI, a 'Super-X' divertor and a full in-vessel cryopump .There will be improved current profile control due to new beam geometry.

These improvements mean that many key expts are possible:

1. Study of low li, k ~ 2.75 regimes (high bootstrap)
2. confinement scaling at high B, low collisionality
3. Beta scans (effect on fast particle modes)
4. B_T scans (effect on neutron emission)
5. NBI heating and current drive
6. Start-up using EBW**
7. EBW heating and current drive**

*** it is hoped to fit EBW at a later stage*

Alternative Tokamak for a neutron source "Fusion-Fission Research Facility (FFRF)"

Zakharov proposes [1] a large, R=4m, a=1m tokamak with shielding to protect superconducting magnets

Vol = $150m^3$, I_p = 5MA, B_T=4T, P(NBI + LHCD) =22-25MW, Pfus =50MW

Lithium walls (tested at PPPL) provide improved confinement

We here concentrate on the smallest design, requiring least tritium – the ST with unshielded centre post

IPB98y,2:

$\tau_E = 0.0562\ Ip^{0.93}\ Bt^{0.15}\ R^{1.97}\ (a/R)^{0.58}\ M^{0.19}\ ne^{0.41}\ k^{0.78}\ P\_in^{-0.69}$

[1] Leonid E. Zakharov 'Basics of Fusion-Fission Research Facility (FFRF) as a Fusion Neutron Source' PPPL-4629